

A Portable, High Resolution, Surface Measurement Device

Curtis M. Ihlefeld, Bradley M. Burns, and Robert C. Youngquist

Abstract—A high resolution, portable, surface measurement device has been demonstrated to provide micron-resolution topographical plots. This device was specifically developed to allow in-situ measurements of defects on the Space Shuttle Orbiter windows, but is versatile enough to be used on a wide variety of surfaces. This paper discusses the choice of an optical sensor and then the decisions required to convert a lab bench optical measurement device into an ergonomic portable system. The necessary trade-offs between performance and portability are presented along with a description of the device developed to measure Orbiter window defects.

Index Terms—Aerospace Engineering, Ergonomics, Optical Sensors, Sensor Systems

I. INTRODUCTION

THERE are numerous launch inspection criteria that must be met in the processing of a reusable space vehicle such as the Space Shuttle Orbiter. One of these is to ensure that the outer windows have not accrued significant damage, both from micro-meteor impacts as well as handling mishaps, and this requires a meticulous search for and measurement of defects. Testing has shown that surprisingly small flaws can result in window pane failure during launch, necessitating surface measurement of suspect defects to accuracies of about 1.5 microns.

During most of the Shuttle program these defect measurements had been accomplished by making a mold of any suspicious spot directly on the Orbiter window. The mold was taken to a laboratory and measured, thus transferring the defect quantification away from the Orbiter environment. Gage repeatability and reproducibility studies have demonstrated limitations with this approach often associated with the mold material not completely filling the defect volume. Consequently, the Space Shuttle Ground Processing Team began searching for measurement techniques that could be

used directly on an Orbiter window to generate a three dimensional map of a suspected flaw.

II. THE CHOICE OF A SENSOR TECHNOLOGY

It was highly desired that any window defect measurement approach be noncontact to minimize the creation of additional damage, so optical, as opposed to stylus approaches were sought. The first consideration was given to microscope based approaches, but these were soon rejected. There was a requirement that the depth profile of a flaw be quantified to an accuracy of at least 3 microns, with a desire to reach 1.5 microns, but the only microscope approaches that provided this level of quantification used small depths of field and relied on a user to determine if the object being viewed was in focus. The problem was that the area being viewed was composed of shattered glass, with wide height variations and multiple sub-surface images, making it nearly impossible to repeatedly determine distances based on focal adjustment. Figure 1 shows a typical Orbiter window defect, probably caused by a low velocity impact, exhibiting variations in focus with depth.



Fig. 1. This is a Space Shuttle Orbiter window defect, most likely caused by a low velocity impact. Approximately, its largest diameter is 0.3 mm and its maximum depth is .04 mm. Such a defect would likely cause an Orbiter window to be scrapped.

Consequently, alternative optical approaches were sought giving consideration to both performance, technical maturity, and the issues to be faced with developing a portable device. An early favorite was laser triangulation. Operational devices

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were on the market at the time of the search (2002-2004) and the potential was high that a portable device could be fabricated, as evidenced by subsequent successes [1]-[3]. Unfortunately available devices at the time did not perform satisfactorily on transparent surfaces, especially ones with the roughened topography seen at the bottom of a defect. Next we considered Mirau interferometry [4], which is currently used in quantifying the mold impressions of the Orbiter defects, but converting this extremely sensitive method into a portable unit where both scanning and vertical tracking would be required was considered too difficult.

The approach we chose was chromatic confocal microscopy [5]-[6]. In this technique broad band light emerging from a pinhole or single mode fiber is focused onto the glass with a lens that has substantial chromatic aberration. This causes different wavelengths to be focused at different distances with only one band being preferentially focused onto the glass such that it reflects and passes reciprocally back up through the lens and pinhole or fiber. The resultant system acts as a distance dependent spectral pass-band filter allowing a high resolution optical spectrometer to accurately measure the distance to the glass reflection site.

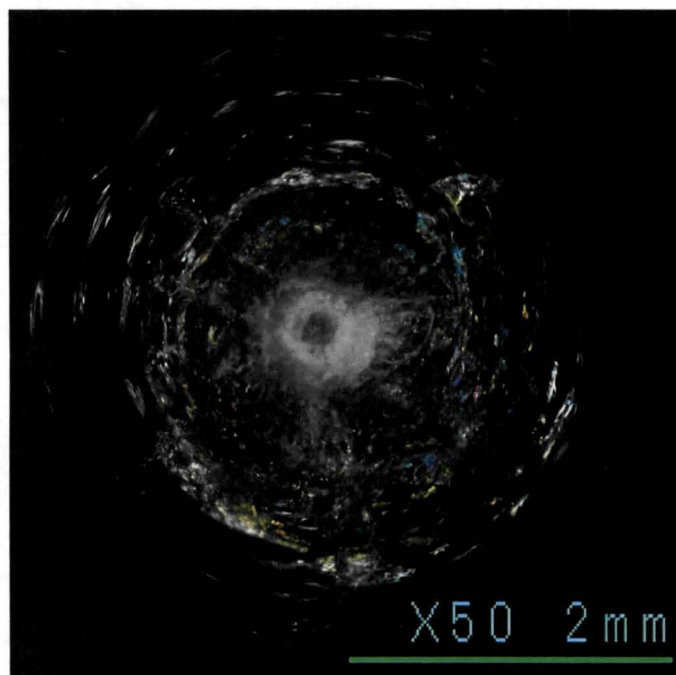


Fig. 2. This is a relatively large hypervelocity (micro-meteor) impact found on an Orbiter window and estimated to be 300 microns deep.

Chromatic Confocal Microscopy was attractive because a variety of compact optical assemblies, i.e., "pens", were available from STIL (Sciences et Techniques Industrielles de la Lumière, www.stilsa.com) along with light sources and spectrometers. We chose a model OP300VM classical optical pen with a measuring range of 300 microns using a halogen bulb light source (our eventual field devices used a white LED which dropped the measurement range to 200 microns) and a glass minimum stand-off distance of 5 mm. This allowed the sensor to be above the glass, but able to see relatively deep

defects (up to 100 microns) and allowed for engineering tolerances in positioning the device. Occasionally very large defects can occur, as shown in Figure 2, but these do not require precise quantification because the window would be declared scrapped by such a defect. The critical depth region, where careful measurement is required to determine if an Orbiter window should be replaced, is 10-20 microns.

The STIL optical pen we chose had an advertised focal spot diameter of 8 microns and axial accuracy of .09 microns, both of which surpassed our requirements, though it was unknown how the pen would function on the shattered glass surface at the bottom of a defect. Also, the numerical aperture of this pen allowed measurements on glass surfaces as steep as 25 degrees off horizontal, providing measurements of many, but not all, locations within a typical defect. Finally, the small size of the optical pen assembly was well suited for a portable sensor, so we proceeded with incorporating this technology into a portable device.

The last technology we considered for quantifying defects on the Orbiter windows was optical coherence tomography [7]-[9]. In this approach broad-band light is launched into a Michelson Interferometer, causing half of the light to reflect off of the defect and the other half to reflect off of a reference mirror, before being recombined and then imaged with a camera. The reference mirror is translated such that the distance travelled between these two paths is less than a coherence length, causing interference fringes to appear in the camera image. By tracking these fringes three-dimensional defect information can be obtained. This approach had the advantage of only requiring one motion axis, the translation of the mirror, but the maturity of the approach was less than that of chromatic confocal microscopy. Because of its potential promise, we are continuing separate research on this technology for future systems.

III. PORTABILITY, ERGONOMIC, AND DESIGN ISSUES

After deciding to proceed with the STIL OP300VM pen to determine the topography of defects on the Orbiter windows, we were faced with the challenge of designing a portable device that a user could place on the window to scan a chosen defect. The scan needed to take as short a time as possible, yet produce a high resolution (spot size less than 25 microns) topographic map of the defect to a depth accuracy of 1.5 microns relative to the surrounding glass plane. The hardware needed to be light-weight and rugged, yet constructed to minimize potential damage to the window. The software needed to produce quality images, calculate parameters, and handle the inevitable sensor data drop-outs that would occur. In addition, we had to ensure that the images and parameters were presented accurately and clearly while not providing misleading information.

The first step was to develop a small, accurate, x-y scanning system and this proved to be unexpectedly difficult due to micron level pitch or height variations in many linear stages.

We tried a variety of stages and eventually settled on using a pair of Newport model 426A, crossed-roller bearing, aluminum stages as the best compromise between performance and weight. We then had to choose between servomotors and stepper motors to drive the translation system and chose steppers because they conveniently provided location information for the pen, yielding adequate performance with simple drive electronics, while occupying a small volume. The completed scanning head of the instrument is shown in Figures 3 and 4. Figure 3 shows the x-y platforms most clearly while Figure 4 shows one of the stepper.

One of the most challenging phases of the design was developing a method to attach the scanning system to an Orbiter window that was acceptable to the end users, yet would not significantly degrade measurement performance. A vacuum based system with suction cups offered a compromise between a pliant, non-damaging, contact to the window and the need for a rigid scanning platform. Concerns remained that the platform would sag during a scan, and that pneumatic vibrations would shake the pen, or that vibrations in the window itself would affect the measurement process corrupting the topographic maps. As a safeguard a rubber sheet was affixed to the base of the scanning head (see Figure 4) to provide an enlarged contact area. This method was successful and no evidence of platform drift or vibration has been seen in any scans.

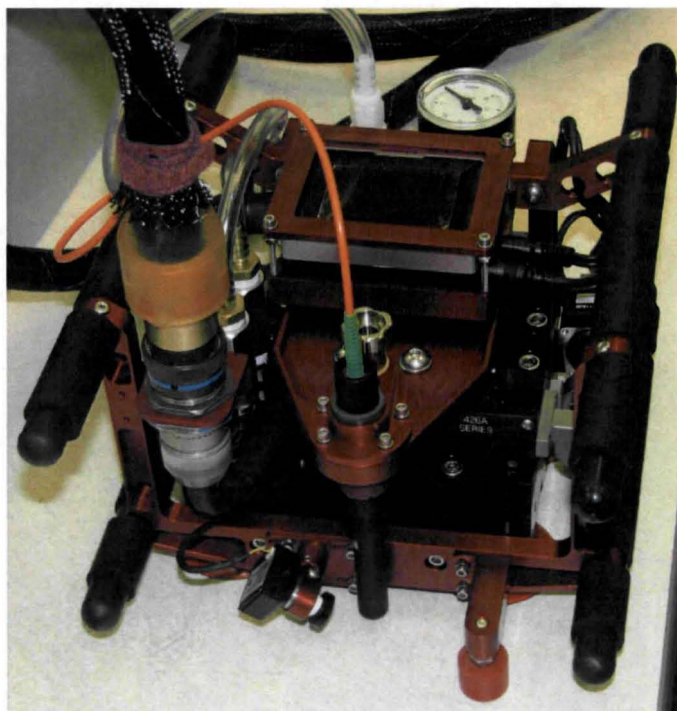


Fig. 3. This is the completed scanning head. A small camera monitors the defect area producing an image to guide the user on the display. The optical pen is shown in front with the orange optical fiber protruding from it. Stepper motors scan the pen across the defect generating the topographic information. The unit is attached to the window with suction cups and the vacuum displayed to the user. Rubber bumpers help ensure that the device cannot damage the window.

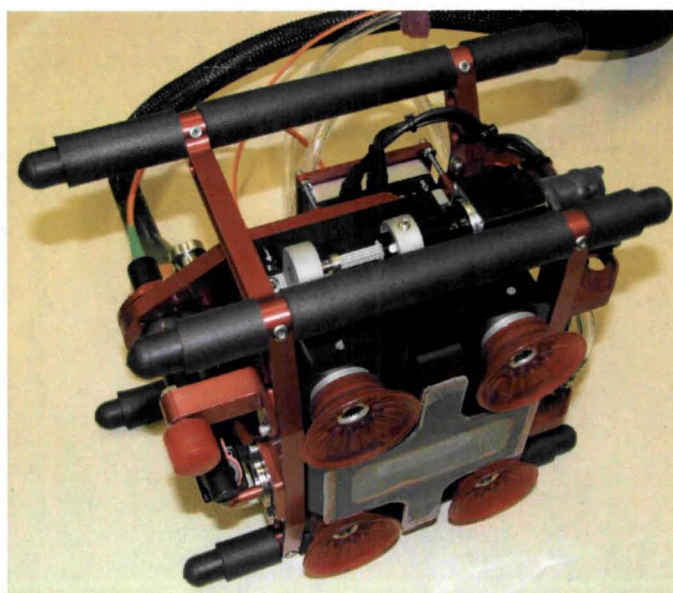


Fig. 4. The underside of the scanning head showing the suction cups and elastomer pad used to secure the hardware to the Orbiter window.

The system needed to be able to scan a specific defect on the window, yet these defects might as small as 100 microns in diameter and difficult to see. To aid in the positioning of the device a small camera is located near the optical pen (see Figure 3) that produces a magnified image on a display attached to the scanning head. In addition, the x-y translation system provides a full 25 mm by 25 mm scan area so the defect only needs to be in that area. The system software can be used to select a small, rectangular region of interest within the camera view and only this reduced area is scanned. To further save time, the user can select the scan resolution, ranging from 2.54 to 127 micron steps allowing a quick, possibly one to two minutes, scan versus a longer, but higher resolution scan.

A custom software interface was developed, with a typical output shown in Figure 5. This program not only allows the operator to select the defect scan area and resolution, but provides real-time imagery of scan being taken. After generating the scan, the software automatically circles the defect and removes surface tilt, generating a flat reference plane from which the defect parameters can be calculated. Parameters include greatest and least dimension, maximum depth, surface area, and total volume missing. Built in cursors allow users to determine the size of selected elements in the defect and users can choose from a variety of data filters whose purpose will be discussed further in the performance section below. The displays to the right of the screen provide additional graphics of the defect, including a shaded two dimensional map of the defect depths with red used to highlight locations where there was no return signal from the optical pen. Final results can be saved in order to build up a data base of Orbiter window defect topographic scans.

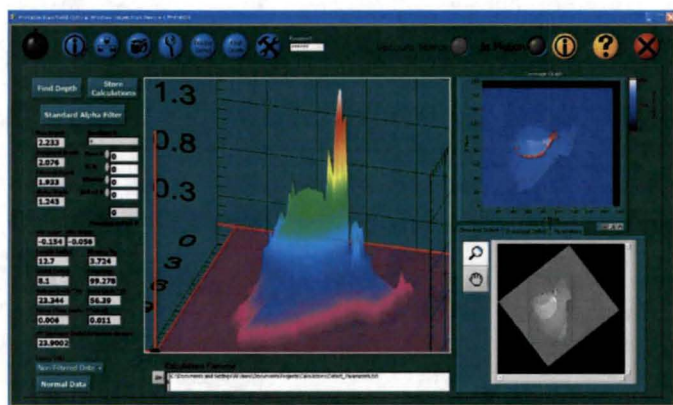


Fig. 5. This is the output screen generated by the surface scanner when looking at the defect shown in Figure 1 (inverted image). Various calculated parameters are shown on the left. On the upper right image data dropouts are shown in red and in the lower right the defect is fit to a rectangle to show maximum and minimum dimensions.

IV. PERFORMANCE

As a first check of performance a set of machined defects were obtained and scanned with the chromatic confocal microscopy head described above and were also scanned with a commercial white light interferometric system. The resulting images were very similar, both technologies producing crisp 3-D images of a small, flat-bottom defect in glass as shown in Figure 6 and both yielding very similar values for the depth of this defect, about 0.9 microns. Of note, both our system and the commercial system appear to overstate the depth of the glass near a steep transition. The commercial system includes filters to minimize the unwanted overshoot causing the measurement artifact. We incorporated user selectable filters into our software, permitting spatial averaging and the discarding of outliers, to provide the same capability if desired.

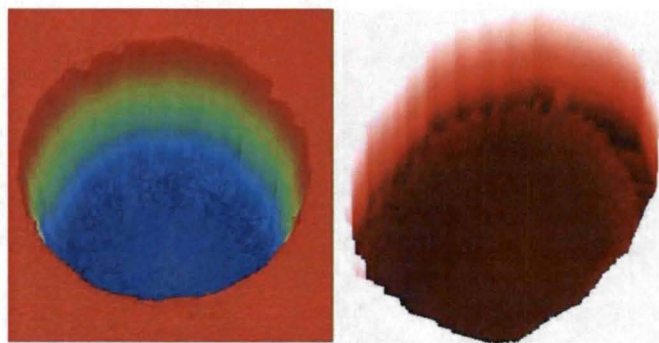


Fig. 6. These are two topographic scans of a machined glass defect. The left one was taken with a commercial white light interferometer while the right one was taken with the portable scanner described in this paper. Both devices provided similar images with nearly identical depth profiles and average depths (about 0.9 microns).

However, filtering of the data raises concerns with potentially hiding a deep but small diameter pit within a defect. Referring again to the defect shown in Figure 1 and scanned in Figure 5 there is a significant and deep artifact shown which happens to

correspond to a large number of missed data points (see the red dot pattern in the small plot to the right in Figure 5). This raises the question of whether this artifact is the result of the over-shoot seen near a steep edge where data is missing, or if there really is a deep pit in the corner of this defect. In this case, enough good data points exist to suggest that there is indeed a pit, but its depth is uncertain. Such cases indicate the limitations of high numerical aperture optical systems when trying to probe into such narrow crevices and care needs to be taken in expecting too much from the instrument in cases of pits with steep edges causing multiple data drop outs.

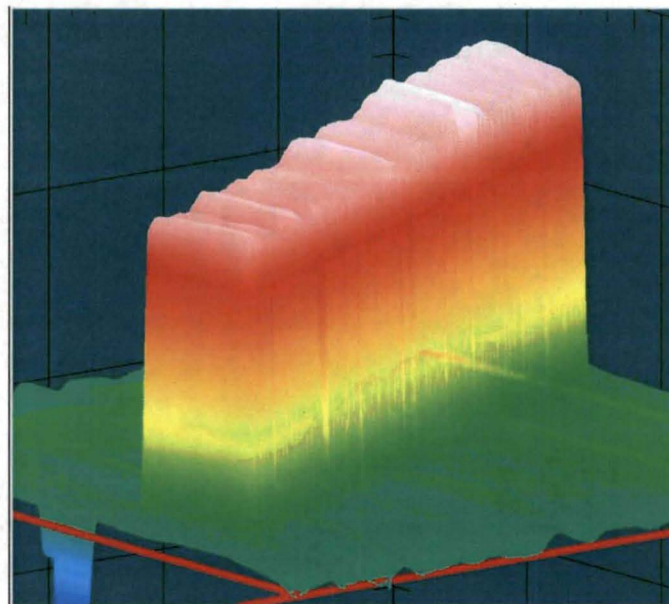


Fig. 7. This is an inverted scan of a glass trough, 10 mm long, 110 microns wide, and 8 microns deep (the length dimension has been compressed to fit the image into the picture). The ripples seen across the top of the trough are believed to be due to bearing variations in the linear stage and correspond to about 0.8 micron peak to peak errors over roughly 1 mm distance ranges.

Figure 7 provides an example of the pitch, or height, variations caused by the x-y translation system. In this image a long (10 mm), narrow (110 microns), shallow (8 microns) trough machined into glass was scanned with the instrument. This image shown in Figure 7 is inverted and heavily compressed in the long dimension showing a roughly 10:1 length to width image rather than the actual 100:1 length to width trough. The ripple seen varying in the length direction, both on the surrounding glass plane and in the trough, is caused by the x-y translation system moving up and down by about 0.8 microns peak to peak along this 10 mm length. This is a limitation in the system for large area scans, but for small defects (less than 0.3 mm across) these broad surface variations are removed by comparing the defect to the surrounding glass surface. This image has been spatially filtering to remove the overshoot problem, but even so, the lack of noise is impressive. Figure 7 is eight microns in height, and there is no significant noise in the image, consistent with the advertised resolution of this STIL optical pen (0.01 microns).

The defect scanning system described in this paper went through a detailed gage repeatability and reproducibility (R&R) study and was deemed acceptable by the Shuttle Ground Processing Program for use on the Orbiter windows. A selection of defects on three scrapped Orbiter windows were examined by three inspectors. It was found that the variation in measurement between inspectors was very low, but that on selected defects that there was some variation with orientation of the scanning head relative to a defect. Upon study, we determined that occasionally the optical pen was returning a signal that appeared to originate below the surface of the glass. Such reflections are well known and commonly seen, but there was concern that their appearance was orientation dependent and that they would generate misleading information. Fortunately, the STIL system is designed so that it can be placed into a mode where two distances are provided corresponding to a first and second reflection. By utilizing this feature we were able to distinguish between the reflection off of the first surface of the glass and the sub-surface reflection, effectively removing this anomalous, yet physical, effect. The final conclusion of the R&R study was that the optical scanning system described in this paper performed better than the historical mold impression approach used by the Shuttle program.

V. CONCLUSION

A portable version of a high resolution, non-contact, surface scanning instrument has been described and its performance demonstrated. This unit has gone through substantial qualification and testing and was only a small step away from being an official part of the Space Shuttle Ground Support Tool Box before the shuttle program was cancelled. Since then, there has been interest in using this device to measure hypervelocity impacts on the many scrapped Orbiter windows in storage, so the devices may still be used for their original design purpose. In addition, we have used this device to scan a variety of other surface defects including machined scratches in steel, sand-blasting pits in paint, and corrosion pits in aluminum demonstrating a breadth of applications.

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REFERENCES

- [1] F. Blais, L. Cournoyer, J. Angelo Beraldin, and M. Picard, "3D imaging from theory to practice: the Mona Lisa story," *Current Developments in Lens Design and Optical Engineering*, August 2008, SPIE Proceedings 7060.
- [2] A. Niel, E. Deutschl, C. Gasser, P. Kaufmann, "A handheld profile measurement system for high accurate wear of railway wheels," *Two- and Three-Dimensional Methods for Inspection and Metrology III*, Nov. 2005, SPIE Proceedings vol. 6000.
- [3] H. Kawasaki, R. Furukawa, "Entire Model Acquisition System using Handheld 3D Digitizer," *Second International Symposium on 3D Data processing, Visualization and Transmission*, 2004, pp. 478-485.
- [4] G.S. Kino and S. C. Chim, "Mirau correlation microscope," *Applied Optics*, September 1990, Vol. 29, No. 26, pp. 3775-3783.
- [5] H. J. Tiziani and H. M. Uhde, "Three-dimensional image sensing by chromatic confocal microscopy," *Applied Optics*, April 1994, Vol. 33, No. 10, pp. 1838-1843.
- [6] G. Udupa, M. Singaperumal, R.S. Sirohi, and M.P. Kothiyal, "Characterization of surface topography by confocal microscopy: I. Principles and the measurement system," *Meas. Sci. Technology*, January 2000, Vol. 11, PP. 305-314.
- [7] E. Beaufepaire and A.C. Boccara, "Full-field optical coherence microscopy," *Optics Letters*, February 1998, Vol. 23, No. 4, pp. 244-246.
- [8] R. C. Youngquist, S. Carr, and D.E.N. Davies, "Optical coherence-domain reflectometry: a new optical evaluation technique," *Optics Letters*, March 1987, Vol. 12, No. 3, pp. 158-160.
- [9] S. Chang, S. Sherif, Y. Mao, and C. Flueraru, "Large area full-field optical coherence tomography and its applications," *The Open Optics Journal*, 2008, Vol. 2, pp. 10-20.